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From Geomimetic to Biomimetic Manufacturing: Digitally Transforming Industry for Sustainability

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Abstract: Digital technologies and Industry 4.0 hold the prospect of improving the sustainability performance of manufacturing, but the environmental implications of this transformation are uncertain. To contribute to resolving the environmental impacts of production, Industry 4.0 needs to be guided by sustainable manufacturing principles. This article asserts that we have access to only one functioning example of sustainable production on planet Earth, which is nature, and that Industry 4.0 guided by natural biomimetic principles can advance sustainable production goals. It first contends that industry to date has been guided *geomimetic* principles—which is the industrial mimicking of physical geologic processes—and that geomimicry is a source of many environmental externalities arising from industrial production. The paper then introduces a series of nature-inspired, biomimetic principles that can be facilitated by the unique capabilities inherent in emerging digital production technologies.

Keywords: sustainability; digital transformation; sustainable production

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1. Introduction

Emergent digital design and production technologies are opening new avenues for sustainable manufacture. However, digital technology is neutral. How it is applied could enhance the sustainability of production or alternatively could accelerate wasteful, toxic, and unsustainable practices. For digital technology to fulfill its promise, it needs to be guided by sustainability principles. One model of sustainable production, and perhaps the only model available on this planet, is nature. The earth's biosphere produces massive quantities of sophisticated products, in the form of organisms, but does so in a way that does not jeopardize the sustainability of the earth. Throughout the history of the planet, organisms have constantly evolved, and the continuous emergence of new species demonstrates that nature fulfills the definition of sustainable development, which is "development that meets the needs of the present without jeopardizing the needs of future generations [1]". Thus, adopting nature's manufacturing principles for the digital transformation of manufacturing is a reasonable approach to enhance its sustainability.

The sustainability subfield of *biomimicry* explores the application of nature-inspired principles to design. The Oxford Dictionary defines biomimicry as "the design and production of materials, structures, and systems that are modeled on biological entities and processes." Biomimicry emphasizes the technological emulation of biological forms and processes that have emerged through evolution [2]. However, the emergence of the digital manufacturing technologies of Industry 4.0 provides new opportunities for applying biomimetic approaches to production.

Scholars have considered the sustainability implications of many Industry 4.0 digital technologies, including additive manufacture/3D printing [3], sensors [4], the Internet of Things (IoT) [5], and Big Data [6]. Recent studies have found that Industry 4.0 can enabling more efficient production, reduce waste, facilitate the reuse of resources, and advance circular economy models [7]. Researchers have further identified the collaboration and the integration of digital technologies into the supply chain to support sustainability transitions [8]. Building on these findings, this article will elaborate five biological principles that illuminate the sustainability of natural production systems and illustrate how digital manufacturing technologies can biomimetically emulate them for industrial production.

However, by arguing that applying digital technologies can advance more sustainable biomimetic manufacturing practices, it leaves a question that has not been answered in the literature, which is, "If we are not engaging in biomimicry in current manufacturing approaches, what are we engaging in instead?" This article asserts that industrial manufacturing techniques are currently based on *geomimicry*.

The term geomimicry has been used sparsely in the literature, with different definitions applied in diverse disciplinary fields. This article will use the term in a novel way, arguing that geomimicry is an implicit basis of human manufacturing up to the present day. It will then make the case that biomimicry can serve as an explicit design context that can enhance the sustainability of the Industry 4.0 transition.

2. Methodology

This study applies a modified biomimicry methodology to the sustainability design questions surrounding Industry 4.0 technologies. Additionally, it extends the mimetic approach to a new domain of physical geological systems. The method of "biomimetics" was first applied to the transfer of biological concepts to technology [9] and has since expanded to embrace social and technological challenges on multiple scales [2]. The goal of biomimicry is not replicating natural forms or processes perse, but instead deriving biology-inspired design principles for problem solving. In terms of applications, it has been asserted that are three types of biomimicry. The first is emulating shape in design considerations, as in copying a shell's conical form for a vehicle. The next is emulating processes, such as replicating a leaf's photosynthesis for energy needs. Finally, designers can emulate at an ecosystem level, as in a city inspired by biology [10]. Examples of biomimicry applications in the literature include the design of products [11] and architectures [12], but there are few examples of biomimicry in systems of production.

Biomimicry methodology begins by (1) identifying the design issue of concern. For this study, the design challenges encompassed the sustainability implications of the commercialization and diffusion of digital Industry 4.0 manufacturing technologies. Investigators then (2) interpret the challenge in terms of biology. This was carried out by evaluating the elements of biological systems that allow them to fabricate organisms in an environmentally sustainable manner over time. Semistructured interviews were performed with biological experts, ecological experts, and industrial ecologists to interpret the design challenge from a biological perspective. Finally, biomimicry researchers (3) identify biological models that offer functions analogous to the desired design outcome. This was carried out by elaborating a series of nature-derived principles that account for the environmental sustainability of biological production interpreted for digital fabrication technologies.

In contrast to biomimicry, geomimicry is an emergent concept and has yet to have a well-developed application methodology. Some early examples include the field of geochemistry, where geomimicry has been defined as the "design and production of materials, structures, and systems that are modelled on geological entities and processes" [13]. Alternatively, in articles about chemical reactions, the term geomimicry is used to describe the development of novel reactions inspired by conditions relevant to geology and as the imitation of principles and conditions of geological systems in the laboratory [14]. In the field of architecture, "geo-mimicry" has been proposed as an architectural methodology to simulate rock formation processes and reproduce geological stratification with the same procedures that guide natural development [15]. Here, an effort was made to translate biomimetic methodology and thinking to the domain of physical geological systems in order to advance the concept of geomimcry more broadly. Table 1 compares the two concepts to illustrate their differences in terms of production systems.

Table 1. A Comparison of biomimicry and geomimicry concepts.

	Biomimicry	**Geomimicry**
System Analog	Natural biological systems and processes	Natural physical systems and processes
Primary fabrication process	Additive manufacture	Subjective manufacture
Design information	Encoded and stored in DNA	Encoded in tangible artifacts
Time frames	Organism lifespans, extinction rates (days–eras)	Oxidation/weathering rates, plate tectonics (years, ages, epochs)
Energy Flows	Solar capture (photosynthesis)	Nuclear decay, gravitational

3. Geomimicry—From the Stone Age through the Industrial Revolution

Geomimicry is defined here as *imitating physical geological processes for the architecture and production of goods.* In this sense, every action of carving a stone, fashioning an iron crowbar, or distilling hydrocarbons is an implicit act of geomimcry. Unlike modern discussions of biomimicry, where scholars are explicitly investigating nature for inspiration and applying it with modern design and engineering techniques, geomimicry is an implicit and emergent process arising initially before humans were scientifically advanced.

Geomimicry can be understood by examining the Earth's geosphere and the operation of geophysical systems [16]. The abiotic, or nonliving, layer of the earth is termed the geosphere and is made up of solid rock and minerals. On the planetary scale, it is composed of continental-scale systems that are driven by plate tectonics [7]. These systems comprise a global process termed the *Rock Cycle* [8], a geology framework that describes how rocks are transformed over time.

The rock cycle is cyclical, so there is no real beginning or ending, but we can start with the formation of igneous rocks, which are created when molten magma cools into solid rock form either on the surface or underground [17]. When plate tectonic forces bring these rocks to the surface, they are subjected to the erosive forces of wind, ice, and water. As igneous rocks are eroded and broken down, they become sediments that can be transported by wind and river systems to sedimentary basins where they settle out into layers. Overtime, these layers become sedimentary rocks [18]. If rocks are buried deep underground or submerged by tectonic subduction, they can be subjected to increasing heat and pressure, which transforms the minerals in the rock as well as the rock structure. The rocks transformed by heat and pressure are known as metamorphic rocks. Human production, from the Stone Age to the Industrial Revolution, has emulated these physical geological processes to manufacture goods.

The earliest examples of geomimicry were ancient humans implicitly copying the Earth's physical weathering processes to produce useful artifacts. As the rock cycle illustrates, physical forces of rain, ice, and wind (along with the force of gravity) are constantly fracturing and eroding geologic terrain. Over time, their influence is substantial, as geomorphic features such as the Grand Canyon demonstrate. Physical erosion and weathering can be considered *subtractive manufacturing processes* [19], and many industrial manufacturing methods fundamentally mimic these processes [20]. The Renaissance artist and sculptor Michelangelo captured the essence of subtractive manufacturing beautifully with his famous quote, "The sculpture is already complete within the marble block, before I start my work. It is already there, I just have to chisel away the superfluous material".

The ancient art of flint knapping is an early form of geomimicry and flaked-stone tool production that dates back over 2.5 million years [21]. Over 13,000 years ago, Clovis point arrowheads [20] were being produced by North America indigenous tribes using subtractive methods. These are examples of humans mimicking the geosphere's erosion processes for the subtractive manufacture of tools. Human techniques and methods evolved over time, becoming more refined with the invention of turning, milling, and drilling tools. However, anytime we use grinding, carving, or whittling techniques to shape an artifact, we are simulating the subtractive processes of geologic weathering. Even modern computer numerical control (CNC) grinders, mills, saws, and lathes depend on geomimicry to subtractively [22] form their products.

Beyond subtractive production, the geosphere also operates accumulative processes that are analogous to human *additive manufacturing* approaches [23]. Take sedimentary rocks, for example. Eroded materials accumulate through sedimentation and accretion, building up layers in an additive process that can become future rocks. Volcanic activity can also produce additive structures. Japan's Mount Fuji stratovolcano, for example, has a beautiful symmetric cone formed by a series of volcanic eruptions that set down lava and ash in sequential layers. These additive processes of geology have been long imitated by humans. Sundried blocks, for example, are one of the oldest human building materials, and are formed by the additive compounding of clay and mud into a mold, which is put in the sun to dry and harden [24]. Early examples of hand-shaped earthenware also depended upon the additive forming of terracotta clays to fabricate containers and figurines [25].

Human additive manufacturing techniques improved dramatically when people began mimicking the pressures and heat occurring in the Earth's crust to forge more durable artifacts. As discussed with metamorphism, buried sediments are subjected to increasing heat and pressure, which transforms them into harder more durable rocks. Humans mimic these conditions in forges and kilns to transform materials. For example, by firing clay in kilns, the constituent minerals are transformed by the intense heat into a technically superior glassy ceramic. The earliest shards of ceramic material have been found in China dating over 19,000 years before present. Over time, human geomimetic methods were refined in way that allowed far greater precision in controlling the heat and pressure of manufacture. By the around 600 CE, humans in China were mass-producing high-quality porcelain containers in kilns for export trade [26]. In terms of building materials, humans were harnessing kilns to subject bricks to the intense heat, which would partially melt clay minerals, resulting in far more robust construction supplies. Fired bricks were first produced in China around 4000 BC and were an important part of Roman engineering techniques [27]. However sophisticated the technology, fundamentally, humans are imitating geologic processes of the rock cycle for manufactures.

Metallurgy is also fundamentally an example of geomimicry [28]. Humans were engaged in metalworking as far back as 40,000 years ago, pounding raw gold and other native metals into useful shapes. Physical metallurgical technologies, however, depended upon melting metal, which in effect required creating plutonic geological conditions at the earth's surface. To smelt metals, temperatures exceeding 1500° centigrade are required, and the first evidence of humans doing so with copper is approximately 5500 BCE [29].

The industrial revolution brought further technological advances that allowed for new geomimetic applications. The exploitation of fossil fuels for energy generation and material manufacture also required the mimicking of geologic forces to fabricate liquid fuels such as kerosene and gasoline, as well as the production of petrochemicals, plastics, and pharmaceuticals. Most chemical industrial processes replicate and control forces that are only found naturally at pronounced geologic depths. These crustal geophysical forces generate natural coal, gas, and oil deposits. Most of the work of a chemical plant is fractional distillation, or fractionation [30], which requires conditions of intense pressure and heat to divide hydrocarbon molecules into component fractions such as kerosene, diesel, and gasoline. These fractional components (along with catalysts) can then be passed through additional industrial processes to fabricate plastics, petrochemicals, and pharmaceuticals, but again, however sophisticated the techniques, these industrial processes are merely mimicking natural geologic phenomenon.

Even nuclear power, perhaps the most sophisticated energy technology, is an example of geomimicry. It is the nuclear heat generated by the decay of radioactive elements that warms the earth's interior [31] and drives plate tectonic activity such as mountain building and seafloor spreading. These same forces also account for surface features such as hot springs and volcanic activity. Geothermal energy production is tapping into these natural flows of geologic heating [32]. In terms of nuclear power, humans select and artificially concentrate radioactive substances on the surface of the earth to generate atomic energy [33]. Moreover, as in the previous examples, even though nuclear power is highly technologically advanced, it is just another example of humans mimicking natural geologic processes.

As the discussion illustrates, geomimicry has been a pervasive element of human production from the Paleolithic Stone Age through to the modern Industrial Revolution. Arguably, the modern material world has been built on the back of geomimetic innovations. However, there are many important environmental externalities arising from our reliance on geomimcry. It is these environmental impacts that are driving much of the discussion about the sustainability transformation of production [34].

4. Sustainability Consequences of Geomimicry

There are many aspects of geomimetic production that foster environmental externalities. Geomimicry's reliance upon natural resources that are extracted from geologic deposits results in substantial environmental degradation [35], including oil exploration and production, mineral mining, and forest logging. These impacts can be seen in some of the earliest human settlements. Many ancient human waste heaps, known in archeology as middens, are filled with the shards of rock wastes that result from flint knapping and the production of arrowheads [36]. Today, resource extraction occurs on an industrial scale and produces large-scale surface disruptions, some of which, such as Canada's Athabasca oil sands, are so widespread that they are visible in satellite imagery [37]. The cumulative environmental impact of resource extraction arises from pollution, ecosystem destruction, species extinction, and loss of ecological services.

Additional degradation further occurs from the manufacturing practices used to transform resources through geomimetic processes. To foster intense geologic conditions in production facilities requires the application of fossil fuels such as coal and petroleum (a Latin and Greek portmanteau for "rock oil"). The conditions produced in industrial facilities and petrochemical plants are not naturally occurring on the Earth's surface, with the exception of volcanic fumaroles, hot springs, etc., such that life in the biosphere has not commonly adapted to tolerate them. The result is that industrial facilities require extensive health and safety procedures to protect humans and the environment. Industrial process can further get out of control, as in the case of an oil refinery explosion, and result in catastrophic and sometimes deadly events. However, there are also slower processes that can accumulate over time, with disastrous consequences.

Geomimicry requires the extraction of materials found within the Earth's crust, sequestered below the surface, and disperses them into the biosphere, atmosphere, and hydrosphere. A large number of these substances are hazardous and often toxic to humans. In addition, geomimetic petrochemical processes can formulate synthetic substances that are foreign to the biosphere, meaning that life is not adapted to deal with them. This can mean that the biosphere is unable to metabolize these wastes, so they can accumulate in the environment, as in the case of persistent organic pollutants (POP) [38]. This persistent detritus of geomimicry creates lasting problems. There are more than 1300 active Superfund sites in the United States, and despite billions of dollars and decades of remediation work, a mere 375 are considered cleaned-up [39].

While Superfund sites are an important problem, the industrial pollution is at least contained in a point source location. However, due to the thermodynamic law of entropy, concentrated industrial chemicals inevitably disperse over time and can dissipate into ecosystems [40]. Some of these chemicals are known to bioaccumulate in the tissue of living creatures, including humans. These chemicals include pesticides, industrial products, and fossil fuel emissions. When these chemicals enter the bloodstream of a living creature, the body protects itself by secreting the toxins away in body fats, a process that leads to the accumulation of the pollutants in tissues. In terms of human impacts, a laboratory testing study of human umbilical cord blood found the presence of over 200 industrial chemicals in newborn children [41]. However, this situation is not limited to humans, as the testing of animals from Arctic polar bears to Antarctic penguins produced similar industrial chemical concentrations in blood samples. The consequences of this geomimetic experiment are currently uncertain, but human health problems such as endocrine disruption and cancer are considered risks [42].

Mimicking the nuclear processes of the Earth also fosters consequences. The explosive release energy from a nuclear bomb is among the planet's most destructive events. Again, however, there is another problem arising from the buildup of depleted nuclear fuels that occurs at a much slower rate. On the surface in the biosphere, nuclear isotopes usually occur in low concentrations, and the resulting natural radiation is often harmless to life in most situations [43]. However, the industrial practice for long-lived spent nuclear fuel has been to concentrate the material and bury it underground. Despite nearly seven decades of work since the first nuclear facility came online, science has made scant progress in resolving the nuclear waste issue. This is an ongoing problem that requires multigenerational vigilance.

Given the extensive environmental challenges arising from industrial production and its geomimetic methods, it is no wonder that scholars are calling for a sustainability transformation of industry. This call has coincided with the emergence of the digital technologies of Industry 4.0 that are opening new production possibilities. It is important that future production approaches do not replicate the problems arising from geomimicry. As the next section discusses, digital technologies appear well suited to adopting biomimetic production principles instead of relying on traditional geomimetic approaches.

5. Biomimicry for Industry 4.0

This section explores five nature-inspired biomimetic principles that can guide the sustainability design considerations for Industry 4.0. The foundational assumption is that the Earth's biosphere is the best model of sustainable manufacture to which we currently have access. It has been functioning for 3.5 billion years of history and its performance has been refined through evolution. Furthermore, it is asserted that many aspects of emergent digital manufacturing technologies are suited to adopting biomimetic design elements. The biomimetic guidelines presented here are inspired from basic ecological [44] and biological [45] principles, following biomimetic design practice. The principles and their correlation with digital manufacturing technologies is elaborated below.

5.1. Biology Is Materially Conservative

The first biomimetic design principle is that nature is materially conservative. In contrast, geomimetic materials engineering has focused on finding novel applications for the geologic resources found in the periodic table of the elements, which encompasses 80 or so elements that occur naturally. The novel materials created by science are picked up by product designers and manufactures to create commercial and industrial goods. The modern Apple iPhone, for example, requires more than 46 different elements, many of which are considered rare earth minerals [46]. In stark contrast, nature has built life primarily using just four elements—carbon, hydrogen, oxygen, and nitrogen (CHON). In addition to CHON elements, life employs trace quantities of calcium, phosphorous, and sulfur to create 99% of life on the planet by weight.

A materials engineer might wonder why the biosphere would limit itself to such a sparse pallet of materials when there are so many other possibilities available in the periodic table. This is perceived as an apparent constraint on innovation. A first response is that being materially conservative has not limited biosphere's creativity. Evolution has fostered an abundance of applications, including a high-tech ceramic in abalone shells that is superior to human equivalents and low-power, portable, cranial supercomputers that we carry in our skulls. The tradeoff benefit of being materially conservative might be the ease it offers in sourcing and applying production resources. The CHON materials are the most abundant on the planet, and all organisms utilize the same materials. Because they are made from the same elements, as long as organisms are present, input resources are always available locally and can be used to fabricate any organism, from a cactus to a condor.

The materially conservative design principle aligns well with additive digital manufacturing technologies of Industry 4.0. Three-dimensional printing technology (3DP), by fundamental design, can fabricate complex forms from a single monomaterial. In 3DP, a plastic polymer such as nylon can be used to form anything from an iPhone case to car parts. The applications are commercially available with 3D printing service companies such as Shapeways, Sculpteo, Xeometry, and others capable of printing thousands of different products, some with very complex geometries and performance characteristics.

Mimicking nature's conservative materials approach would require rethinking input-sourcing choices and product design decisions to dramatically reduce the number materials used in manufacture. The focus would shift from "which materials will allow me to make this product?" to "how can I achieve this design goal with these materials?". By rethinking product design for 3D printing and Industry 4.0, companies could drastically slash the number of materials they use, relying on a handful of key materials to fabricate the bulk of a product, an approach that would mimic nature.

5.2. Biology Is Additive

The second biomimetic principle builds on the previous, which is that nature creates organisms using additive manufacturing processes. While geomimicry depends substantially on subtractive manufacturing, biological organisms are produced, in contrast, using additive processes. The cells in organisms source materials from their environment and use them to grow and divide through the addition of CHON elements to biological molecules. If human industry could mimic this approach, it could result in less wasteful manufacture than subtractive approaches.

Industry 4.0 additive manufacturing techniques are capable of creating objects through progressive deposition of material layers, building products additively from the bottom up. While additive 3DP is still early in its diffusion curve, it has been argued that the technology holds the potential to transform manufacturing [47]. While there has been some interest in utilizing 3DP for biomimicry, the focus of has been on using the technology to mimic complex organic forms. Examples include using 3DP to mimic organic forms in concrete construction [48], creating replacement organs in medical applications [49] or recreating biological forms and materials for commercial applications [50]. However, it is mimicking the processes of additive manufacturing, not the organic forms, that can advance nature-inspired manufacture.

Additive manufacturing, by its nature, facilitates industrial mimicking of the first two biomimetic principles, and in the case of 3DP, producing diverse products from a single monomaterial. While there are many complex technological products that are not currently suited to 3DP, such as the previous mentioned iPhone, there are many others that are already being produced using additive manufacturing, including things such as furniture, architectural structures, clothing, and more. This indicates that there are ample opportunities to advance biomimetic Industry 4.0 production in the near term.

5.3. Biology Is Solar-Powered

The next principle focuses on the energy sources required to achieve the material transformations needed to produce products. Industrial manufacturing uses fossil fuels to mimic geologic conditions and effect transformations. Biology, in contrast, utilizes renewable solar energy to power production processes. In nature, each material transformation, from fox to flower, is driven by solar power. Solar energy is captured through the process photosynthesis which occurs in plant chlorophyll. Trees have hundreds of small solar panels, in the form of leaves, that capture solar energy and use it to fabricate biomass. A tree's captured energy is then transferred to other ecosystem species such as carnivores and herbivores through the trophic pyramid [51]. Biomimetic manufacture would likewise need to run on renewable solar power. This could include wind and hydroelectric energy because these energy sources gain their potency from solar insolation. In the case of hydroelectricity, it is solar heating of water bodies that evaporates and transports water into mountain ranges, and in the case of wind, it is the unequal incidence of solar insolation on the earth's surface that drives weather fronts [52].

The easiest way to mimic this principle is for manufacturing processes to be driven with electricity generated from solar sources. Again, 3DP technology is well suited to mimicking this natural principle, as in most instances, the printing process is powered by electricity. While there are 3DP applications that rely on other energy sources, most production processes can theoretically operate on solar power if the photovoltaic array is scaled appropriate to respond to the energy demand. Renewable-energy-powered 3DP has been demonstrated in early applications [53]. Interestingly, an application of 3DP is the printing of solar cells themselves, something that creates the possibility that 3DP could build out its own infrastructure. Again, this would be an example of biomimicry, as trees fabricate leaves as their own solar panels to power the production of biomass needed for growth.

5.4. Biology Distributes Design Information for Local Production

There are two aspects to this principle: one is the distribution of design information and the other is local production. In nature, the design information that directs the production of organisms is encoded in the DNA found in species genes [54]. This DNA has the benefit of being transported with the organism and is capable of modification through mutations. These attributes facilitate the local manufacture of organisms globally. The information is transported with organisms as they migrate and is used to replicate a new form when the organism grows, sexually mates, or reproduces. The organism then sources CHON resources from its local environment to fabricate a new organism through the application of DNA design information. Again, several capabilities of Industry 4.0 digital technologies allow for the mimicking of these aspects of biology.

Information technology and the internet have made it possible to store design information in a distributed digital repository that can be accessed globally. Cloud computing [55], for instance, relies on networked servers to store and process data remotely instead of on a local computer. Cloud computing has facilitated the emergence of cloud manufacturing [56], a production paradigm that combines globally accessible design information encoded in digital production files in a variety of formats, including AMF, OBJ, STL, VRML, etc., with local on demand fabrication technologies such as 3DP and other manufacturing tools. This capability opens the prospect of mimicking biology. The product file formats encode fabrication instruction analogously to the way the development steps are encoded in genes for living organisms. Thus, product designs stored in a cloud database could emulate DNA in nature, allowing file formats to be digitally distributed globally. This allows for the second principle of local production.

Like nature, digital design information can be made available globally as part of a worldwide production system with local fabrication instead of long-distance product supply chains and distribution. With biomimetic cloud manufacturing, digital files can be downloaded to local facilities where fabrication technologies such as 3DP facilitate local manufacture. These local facilities can be further be run on solar energy that is also generated at the point of fabrication, further emulating natural processes. The final element is that for fabrication to occur locally, production resources needed to be available locally. Fulfilling this requirement is core to the final biomimetic principle.

5.5. Biology Plans Obsolesce

Obsolescence is a fundamental design principle in biology, one that we colloquially term death. Death serves a vital function in allowing life and species to adapt to a changing physical environment and to changing competitive biological circumstances. While obsolescence is fundamental for evolution, it is also important in fulfilling an important aspect of the previous biomimetic principle, that is local production. For local production to occur, fabrication materials have to be locally available. Thanks to the principle of material conservatism, all organisms are constructed of the same raw material inputs. Moreover, because the genes of aging are coded in DNA, their obsolescence is also planned. When organisms die, their materials become available locally to other organisms. When a wolf dies and decomposes, for example, its constituent elements can be picked up on the spot and reassembled into a frog, eagle, or even another wolf.

Again, elements of many Industry 4.0 technologies, if consciously applied, can facilitate the mimicking of nature's planned obsolescence. The first decision refers to the first principle of material conservatism. The fabrication of products using 3DP allows for the manufacture of many different products from a single or small number of materials. In selecting inputs for 3DP, an emphasis needs to be made on selecting materials that can be technically and economically recycled at the end of a product's useful life. Not all materials meet this criterion. Certain materials, such as aluminum, have been shown to have 3DP applications [57], and aluminum is theoretically capable of infinite cycling. It is estimated, for example, that of all the aluminum ever produced, approximately three-quarters is still circulating with no quality degradation [58]. However, plastic polymers, which are commonly used in 3DP, are more complicated and varied in their ability to be recycled.

In some instances, discarded 3D printed products can be ground down into pellets that can be passed through a thermomechanical process and converted back into 3D printing filament [59]. This filament can then be fed back into a 3DP to create a new print. This has been demonstrated in laboratory and field conditions [60] and holds commercial promise. However, most plastics that are processed through a thermomechanical process suffer declines in material performance over time. Each cycle tends to shorten the polymer chains that make up the plastic, making the plastic increasingly brittle [61]. Techniques such as material blending can extend the number of material cycles, but chemical reprocessing is eventually needed to restore the initial properties of plastics. Only select materials, such as polyamides, polyethylene terephthalate, and polyurethanes, have established chemical processing techniques. Thus, chemical recyclability becomes one of the criteria that designers consider while selecting a conservative material fabrication pallet, and one that materials engineers adopt when designing or innovating around polymer materials.

6. Conclusions

It has been argued that the digital technologies of Industry 4.0 are suited to making a transition from the geomimetic industrial production that has characterized human fabrication since the Paleolithic and is arguably responsible for many of the unsustainable practices and accumulating environmental degradation. The new digital tools are neutral, however, and their sustainability impact will depend upon how they are used and the design principles that guide their application. The alternative proposed here is using digital tools to develop a biomimetic global manufacturing infrastructure. There are several suggestions that can help move the digital manufacturing transition in a more sustainable direction. First, like biology, this infrastructure should preferentially be based on products made from of a small number of materials: materials that are capable of infinite cycling, either through thermomechanical or chemical processes. This will simplify the infrastructure needed to mimic natural systems. Second, the design information for production should be digitized and distributed globally through cloud computing networks and made available for local downloading. This would allow for local digital fabrication technology to use the downloaded design information to produce desired artifacts from local materials that are derived by cycling end-of-life products composed of the same conservative, recyclable materials pallet. Finally, a biomimetic fabrication process should be powered by locally generated renewable solar power.

The elements described here have been demonstrated either in laboratory conditions or in commercial applications, making a biomimetic manufacturing infrastructure an attainable alternative to the historic dependence on geomimetic methods. If successfully implemented, it can help ensure that the digital manufacturing revolution is a sustainability revolution as well.

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